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16. Abstract

The Federal Aviation Administration (FAA) Integrated Terminal Weather System (ITWS) is supporting the development of weather products important for air traffic control in the terminal area. These products will take advantage of new terminal area sensors, including Terminal Doppler Weather Radar (TDWR), Next Generation Weather Radar (NEXRAD), and the Meteorological Data Collection and Reporting System (MDCRS). Some of these ITWS products will allow air traffic managers to anticipate significant short-term changes in ceiling and visibility.

This report focuses on the scientific data requirements for supporting prototype model-system development and diagnostics. Model diagnostics can include case studies to determine the most important physical processes that were responsible for a particular ceiling and visibility "event," providing the insight necessary for the development of effective ceiling and visibility product algorithms. In time such case study diagnostics could also include careful off-line "failure analyses" that may affect the design of the operational system. General ceiling and visibility test beds are discussed. Updated reports will be released periodically as the ITWS ceiling and visibility project proceeds.

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ABSTRACT

The Federal Aviation Administration (FAA) Integrated Terminal Weather System (ITWS) is supporting the development of weather products important for air traffic control in the terminal area. These products will take advantage of new terminal area sensors, including Terminal Doppler Weather Radar (TDWR), Next Generation Weather Radar (NEXRAD), and the Meteorological Data Collection and Reporting System (MDCRS). Some of these ITWS products will allow air traffic managers to anticipate significant short-term changes in ceiling and visibility (C&V).

This report focuses on the scientific data requirements for supporting prototype model-system development and diagnostics. Model diagnostics can include case studies to determine the most important physical processes that were responsible for a particular C&V "event", providing the insight necessary for the development of effective C&V product algorithms. In time, such case study diagnostics could also include careful off-line "failure analyses" that may affect the design of the operational system. General C&V data requirements, alternative data sources and candidate sensors for any eventual C&V test beds are discussed. Updated reports will be released periodically as the ITWS C&V project proceeds.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

As currently visualized, Integrated Terminal Weather System (ITWS) Ceiling and Visibility (C&V) products will require the complex integration of a mesoscale model, including four-dimensional data assimilation (4DDA) that will be part of an ITWS gridded analysis system, and a one-dimensional planetary boundary layer (1DPBL) "column" model. Real time data provided by these components of the model system will feed what is expected to be the third part of the triad: short-term statistical forecasts (i.e., one hour "nowcasts") of physically-based C&V products.

The development of both physically-based C&V product algorithms and statistical nowcast techniques will require large amounts of high quality data. In an ideal world, both the C&V algorithms and their supporting parts of the triad system would be developed simultaneously using a large, quality-controlled data set from a test bed that provides a precise three-dimensional description of cloud evolution and resulting C&V degradation. Such a test bed would provide data for statistical forecast model development and validation, while also providing maximum control of data quantity and quality. As well, due to the local nature of the phenomena responsible for C&V degradation, it might be necessary to operate more than one test bed. Each of these test beds, located near the airport center, would operate over a sufficient number of years to gather the quantity of data required for optimal tuning of the system. Other applications for a C&V test bed data (e.g., freezing rain, approach corridor winds, wake vortex advisory system support etc.) may provide a further justification for comprehensive test bed sensor suites.

An attempt is made in this report to reconcile what data sets would be *ideal* with what may be *sufficient* for the development of C&V product algorithms. Since data from even the first of several possible test beds may not become available for several years, this report also discusses alternative data sources, including archived field experiment and real-time data sets. The primary role of archived data sets will be to aid in development of the prototype 4DDA/1DPBL components of an integrated model triad system. Archived data sets will also likely be investigated for use in statistical nowcast technique development. Any statistically-based nowcast technique developed using insufficient data, however, should be thoroughly tested before operational release.

Before launching into a discussion of C&V data requirements, the phenomena that are the primary causes of C&V degradation at several candidate test bed sites will be described. It is necessary to have some understanding about the phenomena of concern to begin to understand the data and sensor suites necessary to capture these phenomena. Several key roles that the data sets will need to play will also be discussed. Since considerable effort has been devoted to technology assessment during the preparation of this report, a list of other institutions involved in developing technologies relevant to the ITWS C&V problem is included as an appendix.

II. PHENOMENOLOGY OF C&V DEGRADATION

Atmospheric visibility is controlled by hydrometeors and the optical thickness of aerosol (which itself is highly sensitive to the sun angle). Hydrometeors include snow, rain, and other forms of precipitation, and fog droplets. At the candidate test bed sites, fog is the most common cause of low visibility significantly affecting commercial aviation. The two primary fog producing mechanisms responsible for these low visibility conditions, radiation and advection, will be discussed later in this Section.

Low ceiling results from clouds with low cloud bases, typically less than 300 m above ground level (AGL). It is only when they exist in an overcast or mostly overcast (broken) condition that they present a potential problem for airline operations in the terminal area. There is some ambiguity in the terminology used to describe the cloud type responsible for low ceiling. Traditionally, cloud classification schemes have included stratus and stratocumulus as separate principal cloud types. This differentiation was mostly based on subjective observations and has come to be viewed as arbitrary. Recent scientific literature on planetary boundary layer (PBL) cloud phenomenology often excludes the use of the stratus cloud type in its terminology, preferring to distinguish only between stratocumulus and cumulus types. Stratocumulus with a low cloud base is the cloud type most often the cause of low ceilings at the candidate test bed sites. In order to be a concern to aviation it usually must result in mostly overcast conditions. Such conditions are often described as a "stratus deck".

The characteristic that differentiates cumulus from stratocumulus is the primary mechanism responsible for their maintenance. Cumulus clouds owe their existence to thermal convection (thermals) caused by heating of the surface. Hence, active cumulus clouds require a large fraction of the sky to be clear to provide the surface heating necessary to maintain sufficient surface heating. Active cumulus clouds show significant vertical development and have well-defined cloud bases. Stratocumulus, however, can also exist as an overcast, as well as showing both vertical development and a well-defined base. A number of mechanisms have been identified that can generate the PBL mixing or turbulence required to maintain stratocumulus as an overcast. The most important mechanisms for stratocumulus over the candidate C&V test bed airports include shear-induced mechanical turbulence and cloud-top radiative cooling. In this report "stratus" will refer to any cloud layer above the ground that results in a ceiling low enough to be of concern to aviation. Stratus can be a result of either stratocumulus cloud with a low cloud base or ground fog that has "lifted" above the surface. Whatever the cause, the resulting "stratus deck" will often have a poorly defined cloud base.

In addition to the citations in the text, several books have provided descriptions of the C&V phenomenology to be discussed in this Section. These include *Storm and Cloud Dynamics* (Cotton and Anthes, 1989), *The Atmospheric Boundary Layer* (Garratt, J. R. , 1992) and *An Introduction to Boundary-Layer Meteorology* (Stull, R. B., 1988).

Description of Primary C&V Phenomena at Candidate Sites

In the development of C&V products, a phenomenology-based approach will be taken. The data needed will focus on capturing the physics of the *dominant phenomena* responsible for C&V events at airports *where C&V degradation is a significant concern.* At the time this report was written, likely ITWS sites included Memphis (MEM), Chicago (ORD) and the New York City (NYC) airports - La Guardia (LGA), Newark (EWR) and John F. Kennedy (JFK). Since San Francisco (SFO) is likely to be a non-Terminal Doppler Weather Radar (TDWR) and non-ITWS airport, its C&V problem may be handled as a separate, special FAA R&D project through the National Science Foundation (NSF). A more precise characterization of the nature of the phenomena important in causing C&V degradation at these airports, through visits and careful analyses of real-time and archived data, is planned. At this time, a reasonable assumption will be made (supplemented by discussions with meteorologists familiar with C&V at the airport) as to the nature of the dominating event(s) at these locations (the independent information source is shown in parentheses):

- **MEM:** Radiation Fog (Dale Dockus, Federal Express Staff Meteorologist)
- **ORD:** Advection Fog (Carl Knable, United Air Lines Manager of Meteorology)
- **NYC:** Advection and Radiation Fog (Dick Eick, TWA Manager of Meteorology)
- **SFO:** Marine Stratus (Peter Lester, San Jose State University Meteorology Professor; Walt Strach, Oakland ARTCC CWSU Chief Meteorologist)

A C&V "event" is defined as either the onset or break up of C&V conditions that significantly change the Airport Acceptance Rate (AAR).

Marine Stratus (SFO)

There have been numerous studies of the spatial and temporal varying structure of the marine boundary layer structure and its associated cloudiness. Some of the more recent include Bridger et al. (1993), Holtslag et al. (1990) and Bechtold et al. (1992). Marine "stratus" is common in the San Francisco central coast region in the late spring and summer months. During these seasons the wind circulation near the surface of the Northeastern Pacific Ocean is usually controlled by a large high pressure area. This results in a northerly (southward) flow along the west coast of central North America. The surface temperature of the ocean decreases as one moves toward land due to forced upwelling. Water temperatures are usually the coldest along the central California coast (often 10 - 15° C). Air, moistened during its long fetch near the ocean surface, is chilled to near its dew point (100 % relative humidity), the temperature at which cloud condensation can occur. During the warm season, the air over the central California coast region is adiabatically heated by widespread subsidence to 30 - 35° C. The air is also usually quite dry, with dew point temperatures typically less than 10° C. The cooler, denser marine layer effectively "slides" under this hot, dry air mass.

Vertical mixing resulting from shear-induced mechanical turbulence lifts parcels to their condensation level. The height at which this occurs is determined by the degree to which the air mass has been moistened before it reaches the coast. Stratocumulus is more likely to be found farther away from the coast while the frequency of stratus (i.e., stratocumulus layers with a cloud base low enough to cause low ceiling) and sea fog is greater nearest the coast where the moistened layer extends closer to the surface and the cloud layer is deeper. Once established, shear-induced mechanical turbulence and cloud-top radiative cooling work together to provide the mixing that maintains the marine stratocumulus layer as an overcast. Cloud-top radiative cooling induces free convection within the PBL by creating "upside-down thermals" of cold air that sink from the cloud top. This mechanism is important, both day and night, whenever no higher-level clouds exist.

The summertime coastal sea breeze circulation increases the onshore component of the flow around the high pressure near the coast. This can bring the marine boundary layer and accompanying stratocumulus layer inland a few kilometers before it evaporates. This distance is greatest just before dawn. The surface is usually dry and warmer than the ocean during the summer months so that the cloud at the lowest levels evaporates, resulting in a stratus layer rather than a surface fog. In the San Francisco Bay area, marine stratus that exists due to this diurnal seabreeze circulation alone nearly always burns off shortly after sunrise. Synoptic and mesoscale disturbances, which have an influence on the height of the inversion, are usually necessary to establish stratocumulus layers of sufficient depth and inland penetration to adversely impact the SFO Airport Acceptance Rate (AAR). At these times cloud (stratus) bases range between 250 - 500 m (800 - 1500 ft) and cloud tops 500 - 800 m (1500 - 2500 ft). Other important factors include the general wind speed and direction and local topography. Marine stratocumulus layers are often horizontally discontinuous, which increases the difficulty of the forecast problem.

Marine stratus in the SFO area is generally a cause of low ceiling; however, foglike conditions and resulting low visibility can also develop as a stratus cloud deck lowers through the nighttime hours, reaching lowest visibility just after dawn. This occurs by a combination of radiative cooling at the top, turbulent mixing within, and evaporative cooling at the bottom of the stratocumulus layer. During strong marine layer intrusions, a diurnal cycling between marine fog and stratocumulus is commonly observed. These factors can also produce alternating bands of stratus and fog called fog streets, and the resulting structure can be carried along by the prevailing wind.

Radiation Fog (NYC and MEM)

Fog results when a moist, stable air mass near the ground cools to its dew point (Bergot and Guedalia, 1994; Fitzjarrald and Lala 1989; Musson-Genon 1987; Duynkerke 1991). Radiation fog forms when the atmosphere within the lowest few meters loses heat to the surface which is being cooled via long wave (terrestrial) radiation to space. Radiation fog requires almost clear skies and a weak pressure gradient. The weak pressure gradient allows for the wind at the surface to become almost calm near sunset. While this

ground fog usually forms as a very stable, shallow surface layer just a few meters deep, under the right conditions it may reach a depth of a few tens of meters and the surface visibility can be reduced to near zero. Once the ground surface is shielded from direct radiative heat loss to space, the upper part of the fog layer becomes the effective radiating surface. Further deepening of the fog layer is usually a result of mixing created by the cloud-top radiative cooling mechanism. A fog layer that has reached this mature, well-mixed stage possesses virtually the same characteristics as stratocumulus. Clear-air radiative cooling in the PBL just above the top of the ground fog layer may also contribute in certain conditions. In total, the depth of the fog layer due to these radiation processes rarely exceeds 100 m.

Advection Fog (NYC and ORD)

Classic advection fog occurs when air passes over cold water or land that has a temperature lower than the air's dew point temperature. It is then chilled to its dew point without any heat necessarily being lost to space. Advection fog is common in the Upper Midwest and can have a major impact on the O'Hare (ORD) AAR. Most airports in the Northeast are affected by advection fog. Advection fog over land is rarely a warm season phenomena. At airports adjacent to the ocean, however, advection fog often originates as sea fog (NYC) which can form at any time of the year. The presence of surface snow or ice can enhance the formation of advection fog. In some cases fog formation can be especially dramatic, with the melting snow actually appearing to be smoking as if on fire. Except in overcast conditions, nighttime radiative cooling usually plays some role. The fog created in these conditions is often called advection-radiation fog. When radiation cooling is not significant, light winds are necessary to provide sufficient vertical mixing to form more than a shallow surface fog. A number of modeling studies have been performed to examine the complex nature of this fog formation process (e.g., Ballard et al. 1991, 1992; Burk and Thompson 1992).

East coast sea fog forms in essentially the same way as central California marine stratus. The main difference is that the air mass is much richer in water vapor (dew point temperatures often above 20° C) and the air is much closer to saturation near the ocean surface. Hence, it is much more common for air parcels to reach their condensation point at a lower level over east coast waters than over west coast waters, which results in foggy conditions. Recent efforts in operational east coast fog forecast modeling can be found in Burroughs (1987). If stratocumulus forms instead, fog-like conditions can still develop as the stratocumulus cloud layer lowers through the nighttime hours by the same process responsible for central California marine stratus. East coast sea fog is also often horizontally discontinuous, which increases the difficulty of the forecast problem. A marine air mass moving inland over a cold or snow-covered surface during winter can accelerate the cooling and the rate of advection fog formation; these events are usually associated with the inland movement of coastal fronts (Nielson 1989).

The most common effect of advection fog on C&V is to reduce the visibility. Under certain conditions, however, advecting sea fog can be transformed to become stratus, at which time the primary C&V problem becomes a low ceiling. A common mechanism for lifting advecting sea fog occurs in the warm season when, after having first formed over the ocean, it moves inland over a relatively warm, dry land surface. Figure 1 illustrates the processes responsible for this transformation. As the cool, moist, foggy air mass advects over the warmer surface, the temperature usually increases above the dew point (relative humidity falls below 100 %) and the fog droplets begin to evaporate. This occurs nearest the surface first.

Regardless of its origin, fog can continue to exist even near the surface if the surface is covered by either surface water or wet snow. The evaporation of dew and transpiration by lush vegetation can also play a important role in maintaining fog over ground surfaces. These conditions result in evaporative cooling and a source of water vapor.

Mechanisms Responsible for Ameliorating C&V Conditions

The formation and maintenance of the fog and stratocumulus phenomena described above usually occurs in the absence of any significant large-scale dynamical forcing. Improvements in the C&V conditions associated with these phenomena that are sufficient to bring the AAR to normal levels often occur well before any dramatic change in this situation. For example, in most cases fog forms and is maintained at temperatures above freezing (warm fog). Less frequently, however, fog can exist as supercooled water droplets in temperatures below freezing. Fog is not as persistent at subfreezing temperatures because fog droplets will rapidly evaporate onto any ice crystals that form. The resulting "snow flakes" quickly grow too heavy to remain suspended and fall out.

The dew deposition process strongly influences the formation of radiation fog. The land surface cools far more rapidly than the air in contact with it and provides a far more efficient surface for droplet formation. The air near the surface usually cannot compete with the land surface in the production of water droplets. Dew, then, is a manifestation of the land surface acting as a water vapor sink. Unless there is sufficient water vapor in the lower atmosphere, it will all go to create dew before the air above the land surface cools sufficiently to reach condensation. This is a less important factor for advective fog since this phenomenon is characterized by the influx of moisture by advection, which continuously replenishes the water vapor supply in the lower atmosphere.

After sunrise the sun begins to heat the surface and the PBL is warmed by turbulent vertical heat flux. The process is virtually identical to that described earlier for the transformation of advecting sea fog into stratus, except that the lower level moisture source is entirely local. During the early phase of this transition, the fog is often described as having lifted. It is during this phase, before the indirect thermal mixing is established, that observations may report stratus (Figure 2).

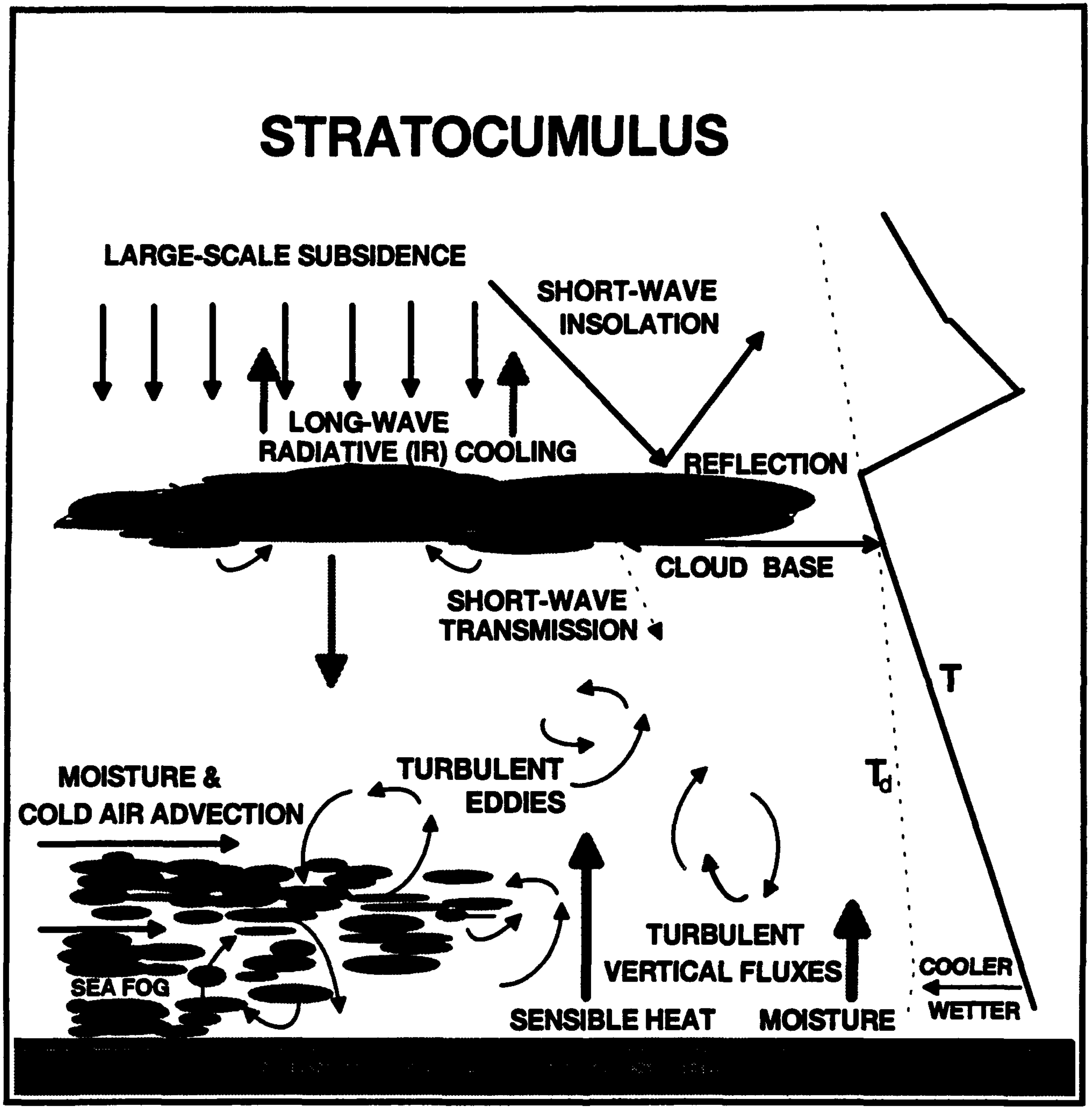

Figure 1. Stratocumulus formed by sea fog advecting over warmer land surface. The vertical dew point and temperature profiles are indicated by T_d and T respectively.

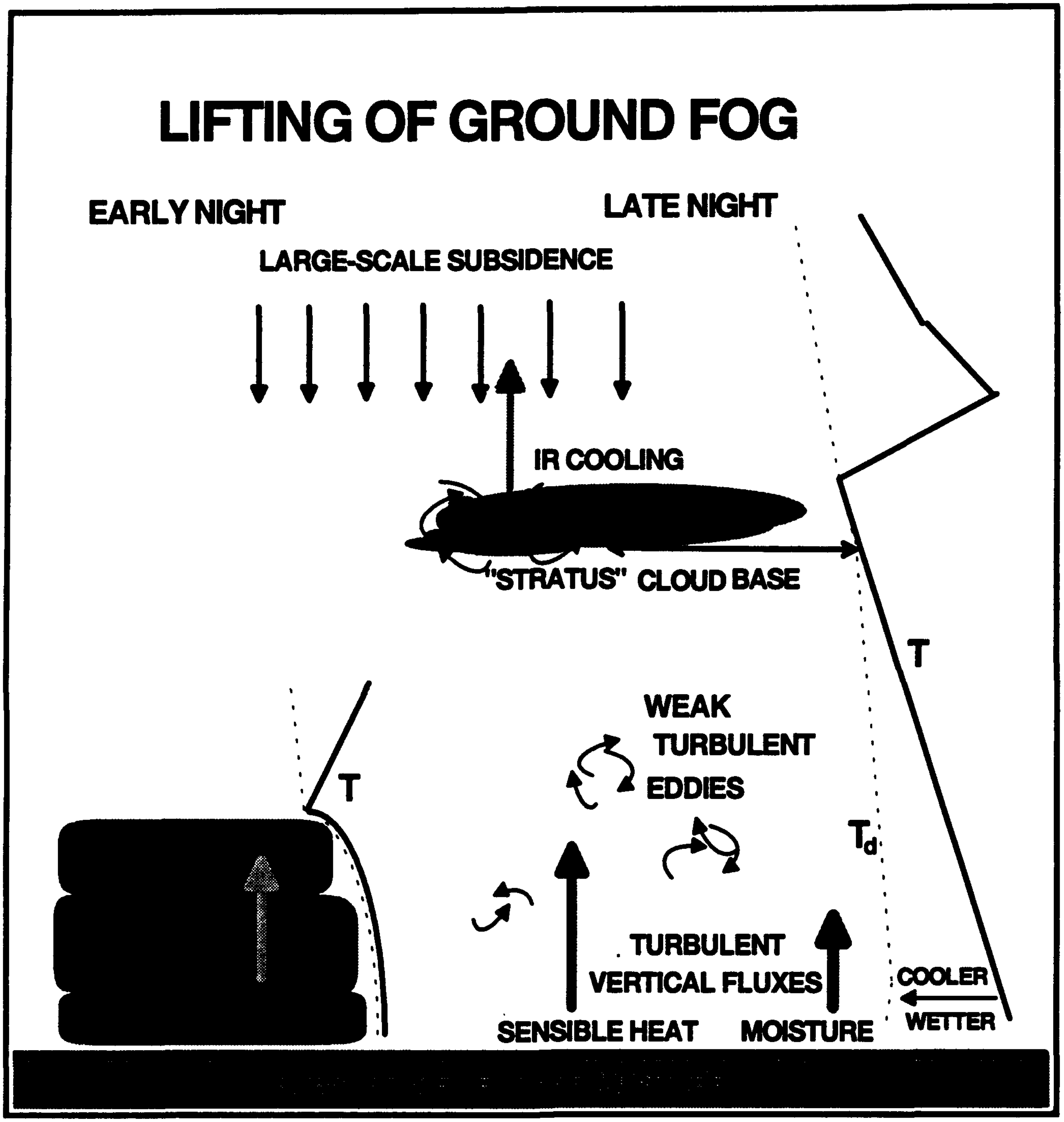

Figure 2. Fog lifting process by short wave radiation heating the land surface and subsurface heat conduction. Labels are as in Figure 1.

The evaporating fog droplets may provide the water vapor for the later formation of higher based stratocumulus or cumulus clouds. Whether fog lifts to form stratocumulus or cumulus is determined by a number of factors. These include the inversion height, the strength of the inversion at the top of the PBL, and the amount of water vapor available. If there is large-scale downward vertical motion (subsidence), the inversion may be below the lifting condensation level (LCL) and no cloud can form. If there is rising motion, cloud will form and the cloud base will depend on the height of the LCL, which depends partly on the relative humidity of the PBL. If a strong inversion exists above the LCL, the cloud that forms will be forced to spread out horizontally, forming a stratocumulus overcast (or nearly overcast) condition. If the inversion is weak, free convection is possible and active cumulus, rather than stratocumulus, may form.

Improvements in the C&V degradation caused by either stratus or fog are often a result of changes, sometimes subtle, of the radiation balance. If ground fog reaches a depth such that the ground surface ceases to radiate to space, heat conducting from below the surface can warm the air in the surface layer and begin to evaporate the fog droplets in the lowest levels of the ground fog layer, improving visibility. For a mature fog layer or stratus deck, high level clouds can play a significant role during either the daylight or nighttime. The existence of higher clouds blocks the normally efficient radiative cooling at the top of the fog or stratocumulus layer so that the PBL warms and the cloud layer evaporates. The cloud layer may also evaporate through cloud-top entrainment instability, wherein dryer air above is entrained into the top of the cloud layer during cloud-top radiative cooling. This may also occur if the development of a nocturnal jet just above the thermally stable nocturnal PBL (NBL) can generate sufficient shear-induced mechanical turbulence.

III. DATA ELEMENTS RELEVANT TO C&V DEGRADATION

From the discussion in the previous section it can be seen that C&V degradation can be related to the formation of PBL cloud. This presents a problem for terminal operations only when the cloud occurs with an unfortunate spatial distribution at an inconvenient time. At candidate C&V test bed sites such clouds are caused by only two or three phenomena associated with stable or weakly unstable PBLs. Thus, many of the data elements listed below are relevant to characterizing the morphology and the equations governing the evolution of PBL structure in general. To develop physically-based ITWS C&V product algorithms, however, those data elements that both quantify the cloud p[illegible]nena and capture the physical processes responsible for its existence must be defined. [illegible]uantifying the amount of either fog or stratocumulus cloud (of most concern at candidate test bed sites), for example, probably the most relevant data variable is liquid water content. Other data would be required to understand the physical processes responsible for its existence, but due to the similarities in these processes and in the atmospheric environment in which they form, most of these data elements will be shared.

Many data elements can easily be measured quantities, but others may need to be inferred using parameterizations. An example would be to use known physical parameterizations that relate visibility to liquid water content. The values thus inferred could be used to evaluate parameterizations of vertical moisture flux convergence. Others, at least as tendencies, must be obtained from numerical weather prediction models. These issues will be addressed more thoroughly in Sections IV and V. The list of data elements included in the discussion below is *comprehensive and idealized*; many data elements may not be included in any test bed supporting off-line evaluation studies. Much of the discussion reflects the consensus of the participants in *The Workshop on C&V Sensor Requirements,* held 2-3 June 1993 in St. Alphose, Quebec. Other sources were Bougeault et al. (1991), Meyer et al. (1986), Noilhan and Planton (1989) and in documentation related to the University of Quebec at Montreal (UQAM) participation in STORM-FEST '92.

Soil-Vegetation Atmospheric Transfer (SVAT) Data

Surface heat and moisture fluxes associated with SVAT processes are likely to be quite important in anticipating fog and stratus events; that is, their onset and break up. These data, either directly or indirectly, provide the lower boundary forcing for the PBL:

- surface type, roughness length and ("skin") temperature
- surface water content (dew, water, ice, snow coverage)
- vegetation canopy water content, capacity and transpiration
- soil heat and moisture flux
- soil temperature and moisture vertical profile
- liquid (rain, drizzle) and solid precipitation rate (snow, sleet)

Several techniques are available that can potentially provide accurate direct estimates of these fluxes. These techniques require net radiation, soil temperature and moisture structure data, as well as soil and surface morphology (including a general characterization of surface vegetation, ice, water, snow, frost, dew, soil heat capacity, conductivity, surface roughness length, sea/water surface temperature, etc.). Parameterizations exist that can be applied to infer these fluxes from state-of-the-atmosphere-variables (SAVs) and other more conventional data (such as liquid and solid precipitation rates), but these should be verified and calibrated using direct estimates. The details of the parameterization for any particular quantity will depend on the nature of the model.

Vertical Atmospheric Profile Data

A familiar example of an atmospheric vertical profile is a sounding, such as is obtained from the operational rawinsonde. Vertical profile data can also be obtained from models; these are sometimes called pseudo- or grid-point soundings. Future references to atmospheric vertical profiles will be in a general sense and can include any information that describes the state of the atmosphere, atmospheric phenomena, or process. For example:

- SAVs (temperature, pressure, wind speed & direction, humidity)
- large-scale vertical motion (especially at the top of the PBL)
- geostrophic wind or large-scale pressure field
- turbulent kinetic energy
- upward turbulent kinetic energy flux
- upward turbulent (sensible and latent) heat flux
- upward turbulent (liquid and vapor) moisture flux
- upward turbulent momentum flux
- cloud condensation nuclei (CCN)
- number and fractional coverage of cloud layers
- cloud base(s) and cloud top(s)
- cloud opacity or visibility
- liquid water content
- net radiation flux (longwave and shortwave)

Figure 3 shows an example of an eddy potential temperature flux vertical profile calculated from the Oregon State University One-Dimensional PBL (OSU1DPBL) model. As was the case for surface quantities, parameterizations can be applied to infer many of those profile quantities that are difficult to measure directly. The large-scale vertical motion at the top of the PBL must be obtained from a numerical weather prediction model.

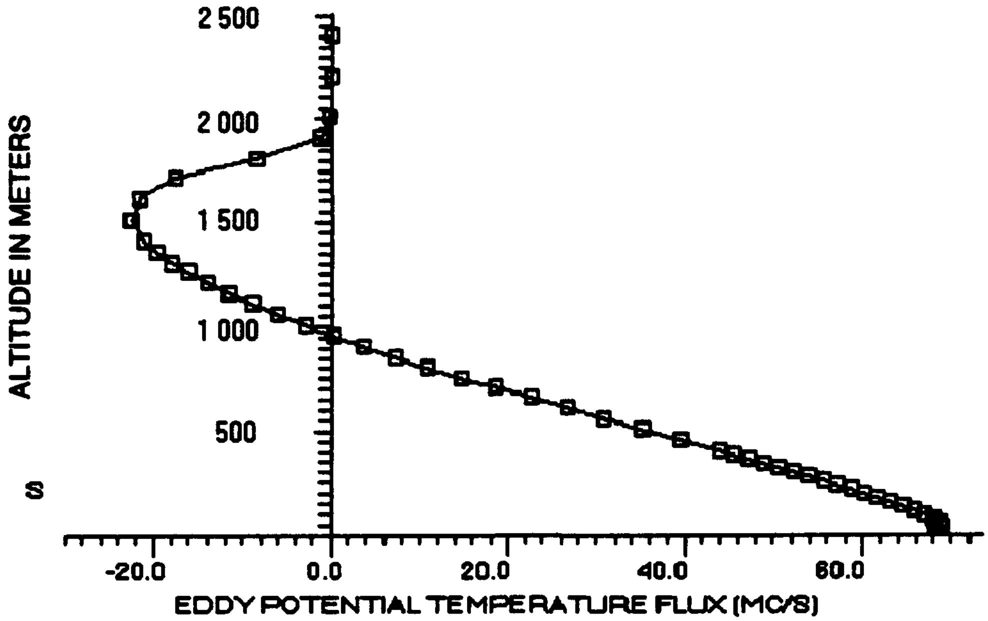

Figure 3. An example of an eddy potential temperature flux vertical profile calculated from the Oregon State University One-Dimensional PBL (OSU1DPBL) model. Flux units are in meters °C per second (mC/s).

Static and Parameter Data

Parameters are required by the data assimilation and analysis system and are generally static in time once sensors are in place. They include, for each data point:

- elevation
- latitude
- longitude

Elevation, latitude, and longitude of sensor or station are required by the data assimilation and analysis system. They are generally static in time, changing only when new test beds are being established or new sensors added, and are determined at the time of the sensor installation. Surface characterization, soil type, and terrain heights (necessary to account for topographical influences) are other examples of a static data. Several gridded data bases exist that might provide these data.

IV. KEY C&V DATA SET FUNCTIONS

In an ideal world, ITWS C&V products would be developed using large quantities of readily available, easily assimilated data sets wherein all physical processes responsible for C&V degradation have been captured completely; that is, all variable data listed in Section III wculd have been measured. Certain important variables, such as vertical heat and moisture fluxes, are included neither in current standard operational data sets nor in many archived field experiments. These must come from some other source. Regardless of the source, while the data will almost certainly fall short of any utopian ideal, they will still be expected to play several key roles during the development of ITWS C&V products. Specifically, they will be expected to support algorithm and operational prototype system development, sensitivity analyses and model diagnostics.

Algorithm Development

C&V product algorithms will need to relate ceiling height or visibility physically to data elements that are measurable by the ultimate operational terminal area sensors. To develop statistical techniques for short-term predictions, or nowcasts, of these physically-based C&V products and to provide necessary truth data sets, large amounts of data should be used. A dedicated C&V test bed provides the most certain way of meeting these needs since the data attributes could be designed for ITWS product specifications.

Operational Prototype System Development

Ultimately, data elements similar to those described in Section III must be made available to algorithms that will *systematically and automatically* generate the ITWS C&V products. Such a system could be designed as a "model triad" that would include a 4DDA system such as T-LAPS, and a 1DPBL column model. Figure 4 shows the data flow for a hypothetical model triad system. As is shown in this figure, the 4DDA might include contributions of a mesoscale model forecast, gridded analysis and a "naive" forecast based on an engineering model (e.g., simple trend, correlation tracker etc.). The column model provides an opportunity to enhance the *site specific* physical processes within the 4DDA as well as adding a predictive capability to the model triad system. In time, similar data sets would be used for failure analyses of statistical nowcast algorithms. Another role for the data sets would be to support "virtual prototyping" by emulating the real-time data flow from sensor systems that will be operational in the future (e.g., uninstalled radar systems, ASOS, MDCRS humidity etc.).

Sensitivity Analyses

Model sensitivity analyses will be necessary to determine the following: which data elements are most important, which can be approximated using parameterizations and which must be measured directly. Potential sensors cover a spectrum ranging from those that are (or will be) operational terminal area sensors (i.e., current and planned ITWS

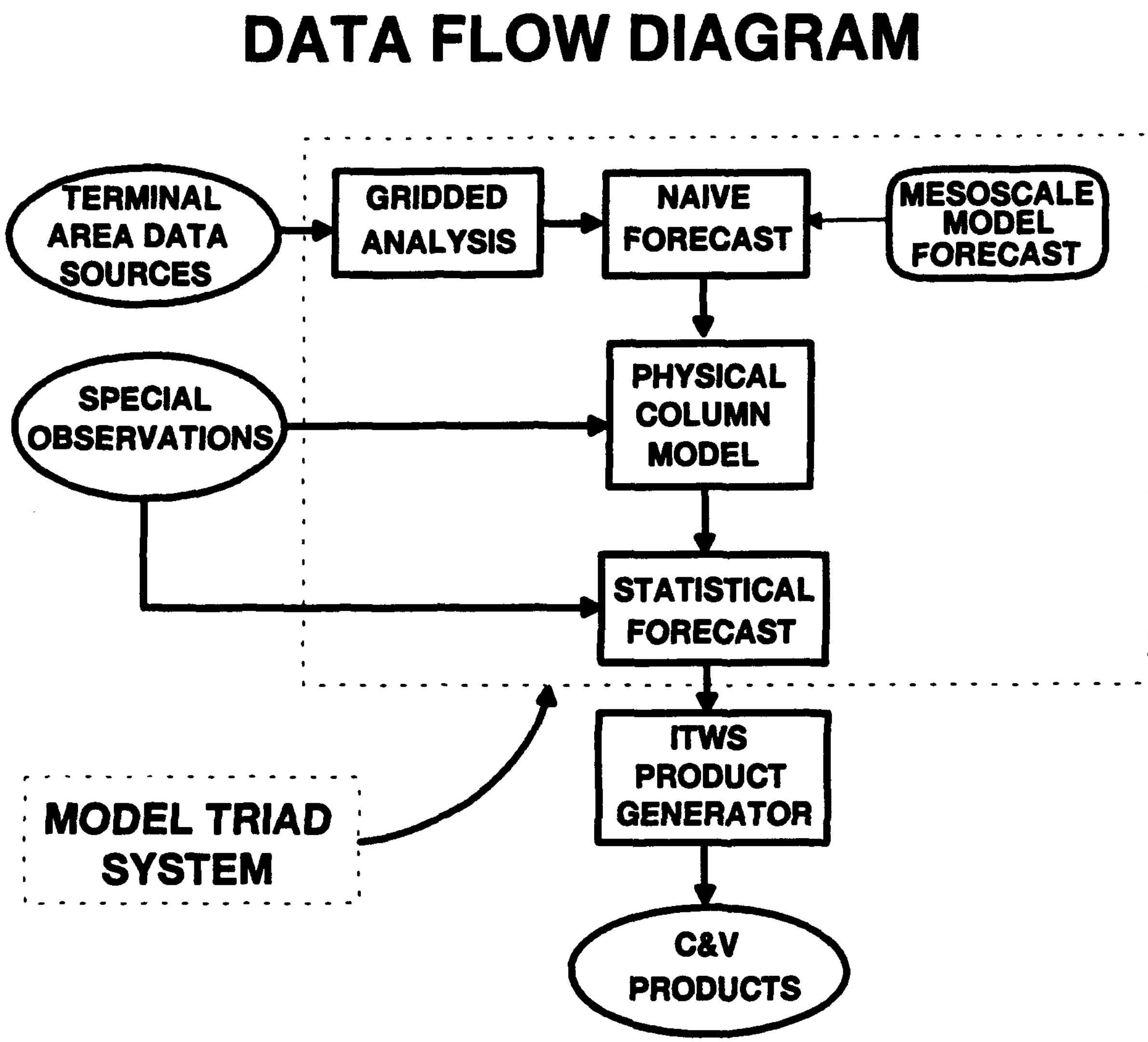

Figure 4. Data flow diagram for a hypothetical C&V "model triad" system.

sensors) to those that are exclusively experimental. "Trade off" studies could also be performed to determine the impact on product accuracy of adding terminal area sensors. This information would be valuable for a thorough cost-benefit analysis of ITWS C&V products and provide the justification for additional operational terminal area sensors. For those data that can be parameterized, sensitivity analyses will aid in optimizing the equation parameters.

Model-System Diagnostics

It will be necessary to do off-line model-system diagnostic case studies to understand the physical processes that occurred during particular C&V degradation events. These data could also be used to help answer some important questions that relate to determining the optimal specification of the model triad and its parameterizations, including:

- What are the most critical physical processes that govern the behavior of important local terminal area C&V phenomena?
- Can those processes not captured directly in the operational terminal area sensor data be inferred using parameterizations?
- What minimum temporal data update rate is required to detect changes in C&V?
- How useful is mesoscale model output (e.g., MAPS or NGM)?
- What is the most effective vertical coordinate for the model triad system?
- How much value *is* added by implementing a site-specific physical column model?
- What is the appropriate horizontal scale for representing C&V in the terminal area?
- Can mesoscale model forecasts be used to update column model parameterizations?

V. POSSIBLE DATA SOURCES FOR ITWS C&V PRODUCTS

Terminal area C&V test bed sensor suites will probably include current or planned operational sensors, special sensors that may be necessary for operational C&V product support and experimental sensors for product development and validation. The technical details for the actual design of a C&V test bed will be provided in a future report. Before proceeding to design a C&V test bed, however, archived data sets from previous field experiments interested in capturing similar physical processes will be investigated.

Sensor Systems

Sensor suites will be designed to support C&V products that are appropriate for the terminal area of concern. These sensor suites will likely consist of both individual sensors and sensor *systems* that will be integrated into a sensor suite for a specific ITWS site. According to Stull (1988) sensor systems for PBL measurements may include as many as six components:

- detector (or sensor)
- encoder or digitizer
- data logger
- instrument platform
- calibration device
- display device

Sensor systems may also include a number of sensors on a single platform and communication network.

Individual sensors can also be divided into two fundamental classes: direct and remote. Direct sensors are those that are placed on some measurement platform and make *in situ* measurements at the sensor location. Remote sensors make measurements at a distance from the sensor location based on either an active or passive remote sensing physical principle. Active remote sensors generate their own waves using a transmitter and use a receiver to capture these waves upon their return. The value of the variable measured is determined largely by how these captured waves have been modified.

Table 1 shows a summary of possible terminal area C&V test bed sensors that include current or planned operational sensors, special sensors that may be necessary for operational C&V product support and experimental sensors for product development and validation. Further information on these sensors is included in Tables 2 through 4. These figures show, respectively, current and planned operational terminal area data / sensors, possible special observation sensors for ITWS C&V product support and C&V test bed sensors for product validation and off-line development.

Table 1. Possible operational and test bed C&V sensors / platforms.

TERMINAL AREA (OPERATIONAL)	SPECIAL (FOR C&V PRODUCT SUPPORT)	OFF-LINE PRODUCT DEVELOPMENT AND VALIDATION
ASOS Rawinsondes TDWR NEXRAD MDCRS Mesoscale Model Data	Expanded ASOS Enhanced ASOS Sodar Buoys Environmental Satellites	Research Mesonet Net Radiometers Hydrological Probes Gerber LWC Microwave Radiometer CLASS Tethersonde Profiler/RASS K-Band Radar Droplet Spectrometer Instrumented Tower Instrumented Aircraft

Table 2. Current and planned operational terminal area data / sensors.

SENSOR SYSTEM	DATA ELEMENTS	HEIGHT RANGE	VERTICAL RESOLUTION	COST#
ASOS	SAVs, Visibility, Cloud Height & Coverage, Precipitation Type & Rate	Surface Only	NA	None
Rawinsonde	SAVs	Surface to 10+ km	100 m	None
TDWR	Radial Wind Velocity & Reflectivity (Base Data)	Variable (60 km Range)	Variable	None
NEXRAD	Radial Wind Velocity & Reflectivity (Base Data)	Variable (120 km Range)	Variable	None
MDCRS	Temperature, Wind (Humidity later)	> 100 m	100 - 700 m	None
Mesoscale Model Data	SAVs, Large-Scale Vertical Motion, Temperature Advection and Upper Boundary Conditions	Surface to 10+ km	25 - 500 m	None

#: Additional cost, not including system engineering, communications, etc.

Table 3. Possible special observation sensors for ITWS C&V product support.

SENSOR SYSTEM	DATA ELEMENTS	HEIGHT RANGE	COST#
Expanded ASOS	Standard ASOS SAVs	Surface Only	None
Enhanced ASOS (Standard ASOS, Net Radiometer & Hydrological Probe)	Standard ASOS SAVs plus Net Radiation, Soil Temperature & Moisture	Surface Only	See Table 4
Sodar	Mixed Layer Height	0 - 1000 m	$25K+
Buoys	Ocean Surface Temperature	Surface Only	None
Landsat satellite	Surface Albedo, Type, Soil Moisture & Temperature	Surface Only	None

#: Additional cost, not including system engineering, communications, etc.

Surface Sensor Systems

Surface sensor systems generally measure the so-called state-of-the-atmosphere variables (SAVs) of temperature, pressure, humidity, wind speed and wind direction. These "SAVs" are standard inputs required for many calculations in physically-based diagnostic models for both fog and stratocumulus. Some of these sensor systems, however, also provide additional data for inferring other quantities important to C&V.

- Operational Automated Surface Observation System (ASOS)
- Expanded ASOS
- Enhanced ASOS
- Research mesonet
- Buoys

ASOS, an upgrade to the Automated Weather Observing System (AWOS), has been designed to replace the manual Surface Aviation Observation (SAO) and is currently being commissioned by the FAA for over 1000 sites in the U.S. Operational ASOS data (consisting, depending on the data element, of a two- to five-minute average) is available each minute. ASOS stations collect SAVs plus visibility, cloud height, and precipitation type and rate. At FAA airport locations, the ASOS sensor will provide the National Weather Service (NWS) standard measure of visibility and pass through the legally mandated Runway Visual Range (RVR) sensor data.

Table 4. Possible C&V test bed sensors for product validation and off-line development.

SENSOR SYSTEM	DATA ELEMENTS	HEIGHT RANGE	VERTICAL RESOLUTION	COST#
Research Mesonet (High Area-Density Coverage)	Standard ASOS SAVs plus Net Radiation, Soil Temperature & Moisture	Surface Only	NA	About $40K
Net Radiometer	Net Radiation	Surface Only	NA	Less than $10K^L
Hydrological Probe	Soil Temperature & Moisture	Surface & Subsurface	Variable	About $5K
Gerber Cloud Liquid Water Content (LWC) & Equivalent Droplet Radius (R_e) Sensor	Liquid Water Content, Effective Droplet Radius	In Situ	Variable	About $20K
Microwave Radiometer	Total Moisture	Vertically Integrated	NA	Less than $10K^L
CLASS	SAVs	0 - 10+ km	25 m	Variable
Tethersonde* (Platform)	Temperature, Wind & Humidity	To 400+ m	6 Levels	$38K
RASS (2 KHz)	Temperature	100 - 1000 m	105 m	$25K^L
Profiler (915 MHz)	Wind, Turbulence	100 - 2000 m	220 m	$125K+^L
K-Band Radar	Cloud Layer	Variable (25 km Range)	Variable (User Specified)	$250K
Instrumented Tower (Platform)	Most In Situ Sensor Data Elements	0 - 60+ m	1 - 10+ m (User Specified)	$15K

#: Not including system engineering, communications, etc.
*: Not usable if wind speed exceeds 5 m/s
L: Lease options available

The primary purpose of a supplementary surface mesonet would be to provide truth data sets for procedures using ASOS data. Examples of surface automated mesonets include the NCAR Portable Automated Mesonet (NPAM) and the NOAA Environmental Research Laboratory (ERL) Atmospheric Turbulence and Diffusion (ATD) Division Portable Mesonet. Besides SAVs, both systems collect precipitation data; the NOAA ERL ATD system also measures solar radiation. Data are available as one minute averages, except for precipitation, which is a one minute total.

Many of the data elements available in research mesonet systems are also available from ASOS. Since ASOS is designed to be expandable, by increasing the number and coverage of systems it would be possible to create an "expanded" ASOS network. In addition, by adding *special observation* sensors, an "enhanced" ASOS network could be created that functions as an operational automated mesonet.

Sounding Systems

Sounding systems measure the SAVs of temperature, pressure, wind speed and direction, and humidity as a vertical profile. Candidate sounding systems include:

- Operational rawinsondes
- Operational Meteorological Data Collection and Reporting System (MDCRS)
- Acoustic sounder (sodar)
- Cross-chain Loran Atmospheric Sounding System (CLASS)
- Profiler
- Radio Acoustic Sounding System (RASS)
- Tethersondes
- Instrumented Towers
- Microwave Radiometers

The only current operational sounding system is the National Weather Service (NWS) rawinsonde network. It was designed to resolve synoptic scale circulations (horizontal scales greater than 500 km); however, careful analysis techniques can resolve smaller scales. Operational rawinsondes are generally released every 12 hours. MDCRS data from the Aeronautical Radio, Inc. (ARINC) Aircraft Communications Addressing and Reporting System (ACARS) can currently provide vertical temperature and horizontal wind profiles during descent in the terminal area. Before the end of the decade, moisture and vertical acceleration (which can provide an estimate of turbulence intensity) are expected to be included under the Commercial Aircraft Sensing Humidity (CASH) program. Currently, the sampling rate provides a rather coarse 2000-feet vertical resolution, but an increased sampling rate would not be a problem, technically. Sodar systems can detect the height of the interface between the PBL and the free atmosphere. Unfortunately, they have a maximum effective vertical range of 1 km, so that they are not very useful except at night and in the early morning.

Local Adaptation of Data/Sensor Systems

Since it is to be expected that each potential test bed site will have its own unique meteorological characteristics, a sensor suite will need to be tailored for each specific site. As an example, consider the San Francisco TRACON region (SFO). While not a TDWR airport, it may become a non-TDWR ITWS airport. SFO is an example of a location where the airport capacity problem is due to a single phenomenon, low ceiling. This

phenomenon is caused by marine stratocumulus associated with the coastal sea breeze circulation. The coastal sea breeze circulation is virtually a daily occurrence for up to five months of the year (May through September) in most years. On occasion, stronger than usual intrusions of the stratus layer occur that can cause persistent low ceilings that significantly reduce the SFO AAR.

A preliminary evaluation of the SFO situation, and consideration of a possible algorithm, has suggested the mix of sensors shown in Table 5. The approach involves keeping track of the depth of the stratocumulus layer, monitoring the net radiation balance and using a column model to anticipate the time that the layer will evaporate. Existing operational sensors, except for the Oakland Rawinsonde, possess the potential to support a model system with significant data rates. The net radiometer and sodar sensors would be able to provide an enhanced level of data for a relatively low cost (Tables 3 and 4).

Table 5. Possible SFO test bed suite.

EXISTING OPERATIONAL	ENHANCED OPERATIONAL	VALIDATION
ASOS (Ceilometer)	Net Radiometer	Profiler
MDCRS	Sodar	RASS
Rawinsonde (at Oakland)		K-Band Radar
Buoys		

Alternative Data Sources

While the most direct way to obtain the data sets listed above is from a test bed over which MIT/LL has direct control, there may be external sources of data that can be used. It is of interest to both determine the information content of currently available data sets and to take advantage of field experiments planned in the near future to address phenomena needing data sets similar to those required for C&V. This is especially true for those experiments that were focused on the same physical processes.

Field Experiment Data Sets

A number of field experiments have been performed within the past ten years that have potentially useful data sets. These data sets have been archived and should be accessible through either internet UNIX file transfer protocol (ftp) or conventional media. These include:

- *Fitzjarrald/Lala FOG-82* - Extensive cooperative field study of radiative fog during the fall of 1982 lead by the Atmospheric Sciences Research Center, State University of New York (ASRC/SUNY/Albany). A complete description of the FOG-82 test bed design can be found in Meyer, et al. (1986). The sensors and data included in the FOG-82 study are shown in Figure 5.

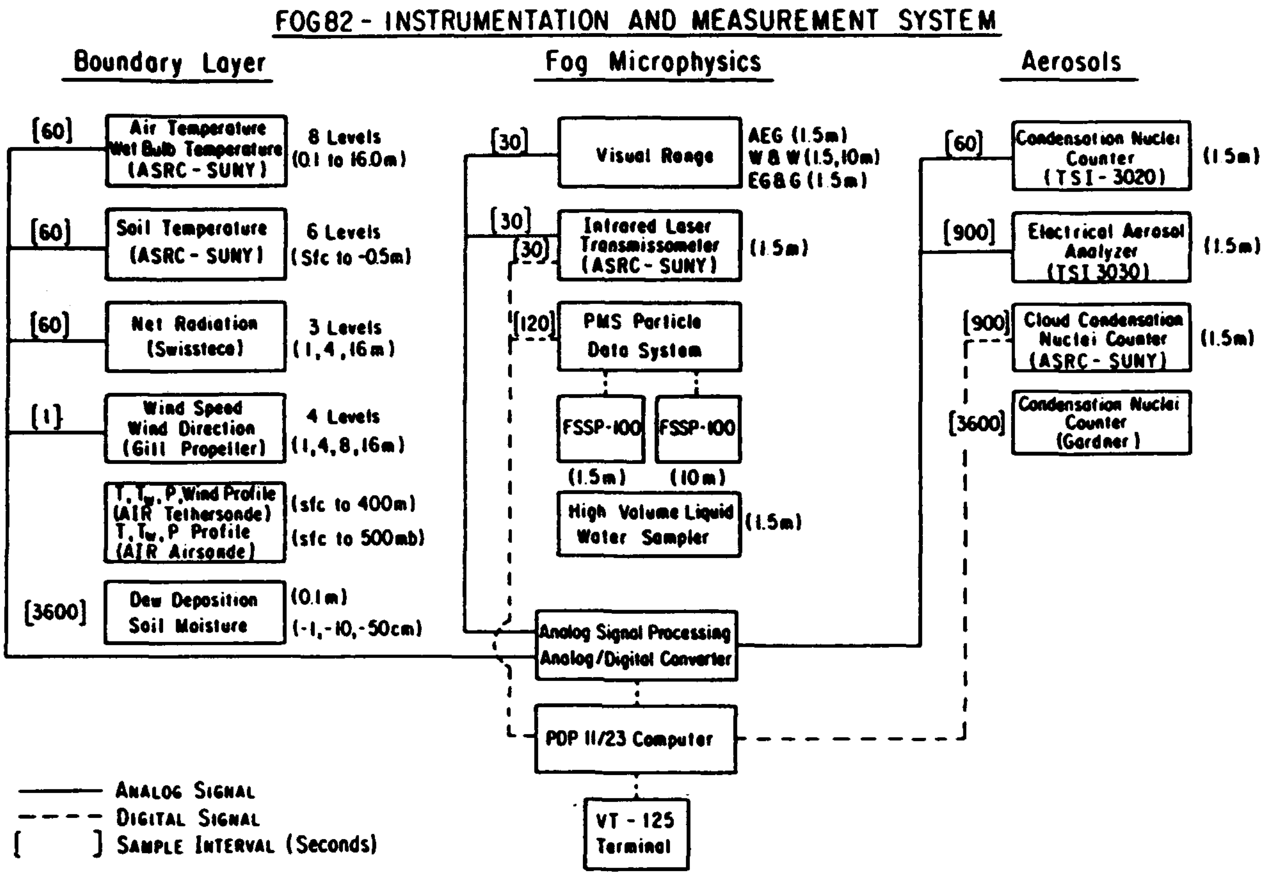

Figure 5. FOG-82 instrumentation and measurement system (from Meyer, et al.1986).

- *Lille Radiation Fog Test Bed* - Operated by Meteo France during the late 1980s and early 1990s near Lille, France. Data collected for input for radiation fog forecast system using column model nested in operational mesoscale model and for validation. A map of the test bed region is shown in Figure 6. This region is covered by a network of automated observing systems similar to the US ASOS. Table 6 shows a summary of the sensors and data collected during two "campaigns" (IOPs) at the primary site near Lille.

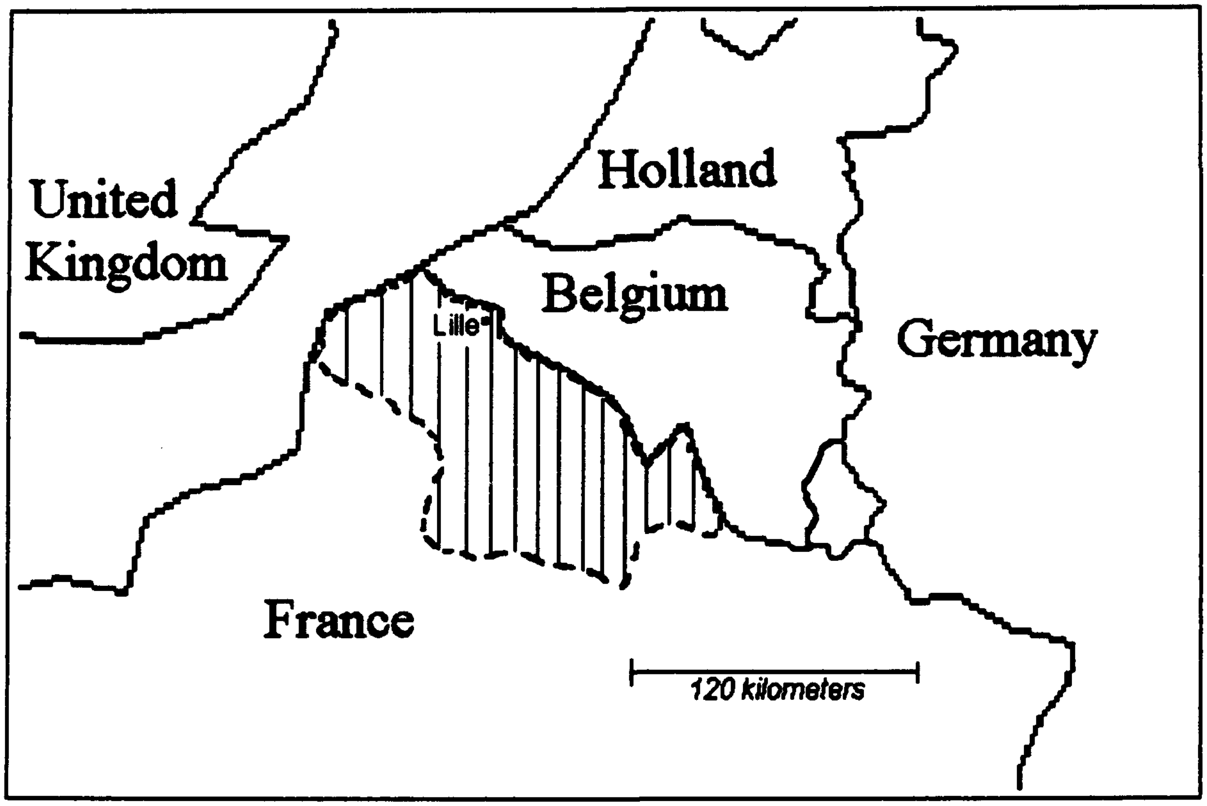

Figure 6. The Meteo France radiation fog test bed (hatched) and surrounding regions.

Table 6. Sensors and data collected during two intensive observation periods (IOPs) at the Meteo France primary radiation fog test bed site (Lille, France).

	ALTITUDE (m)								
VARIABLE	**80**	**45**	**20**	**10**	**5**	**2.5**	**1.4**	**0.7**	**0.3**
Air Temperature	+	+	+	+	+	+	+	+	+
Wind Speed	+	+	+	+	+	+	+	+	
Wind Direction	+	+	+	+	+		+		
Solar Radiation	+						+		
Infrared Radiation	+						+		
Horizontal Visibility							+		
Atmospheric Humidity	+	+	+	+	+	+	+	+	+
Cloud Liquid Water Content	+	+	+	+	+	+	+	+	+

- *STORM-Fronts Experiment Systems Test (STORM-FEST '92)* - First field test of the US Weather Research Program (USWRP). Data for background research leading to the upcoming STORM I Multiscale Field Experiment in 1995 over the central U.S. Figure 7 shows the various STORM-FEST '92 surface sensor system locations and Table 7 shows the data elements included. Figure 8 shows the STORM-FEST '92 upper air sounding stations for the inner network.

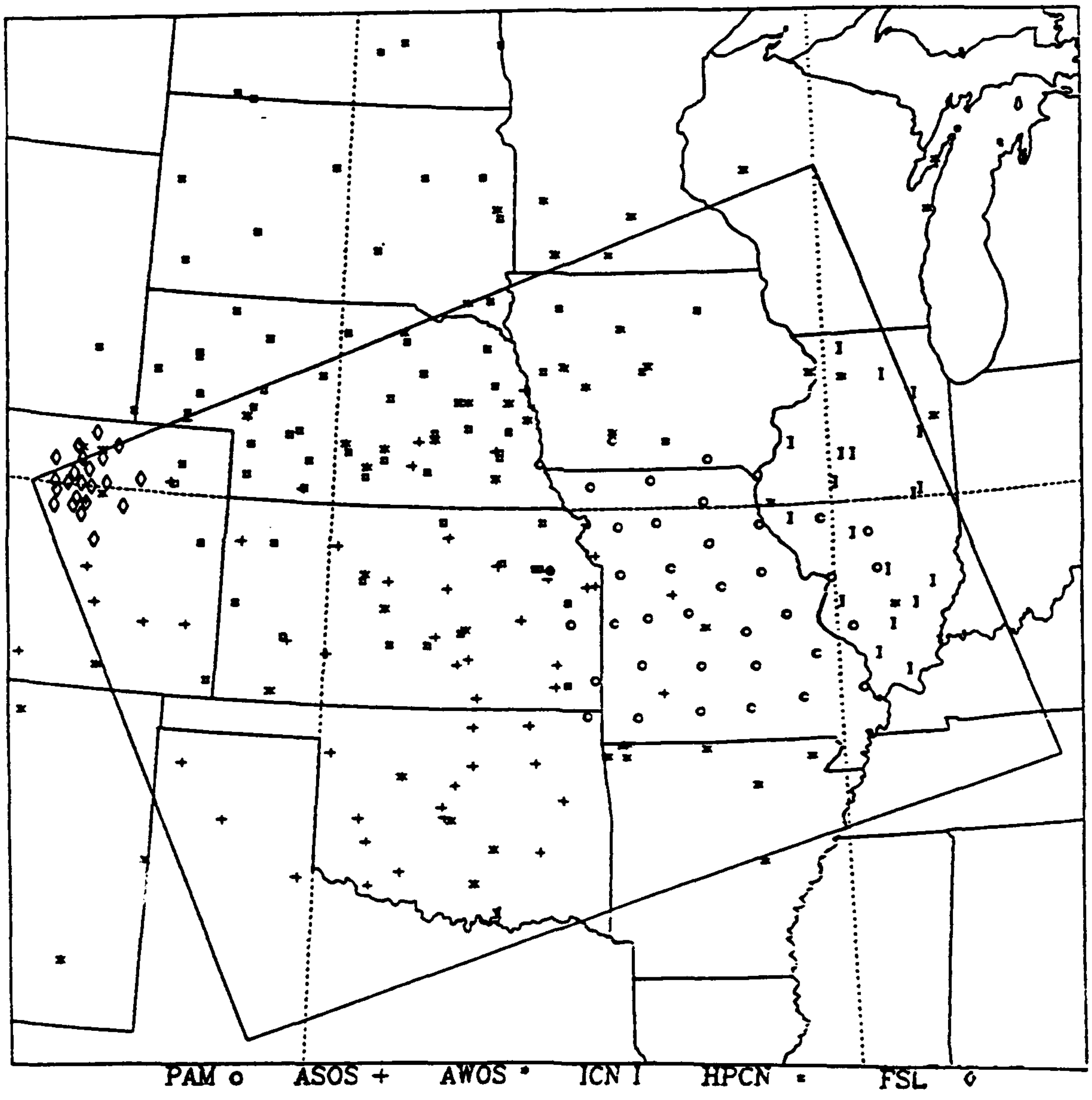

Figure 7. STORM-FEST surface station locations shown for the NCAR Portable Automated Mesonet (PAM), Automated Surface Observing System (ASOS), Automated Weather Observing System (AWOS), Illinois Climate Network (ICN), High Plains Climate Network (HPCN) and the NOAA Forecast Systems Laboratory (FSL) network.

Table 7. Summary of STORM-FEST surface data sets archived by the National Climate Data Center (NCDC).

NCDC SURFACE DATASET DESCRIPTION

DATASET NO.	DATASET NAME	OBSERVATION SCHEDULE (Local Time)	DATASET PARAMETERS
TD-3200	Summary of the Day (Cooperative)	Daily; Variable Times: (most 7A to 7A or 7P to 7P)	Temperature (min/max)*, Precip(24-h)*, Evap (amt), Soil Temperature, Wind(24-h movement) * *most stations only report*
TD-3210	Summary of the Day (First Order)	Daily; 2400 to 2400	Temperature(min/max/mean), Relative Humidity(avg), Dew Point Temperature(avg), DegDay(heat/cool), Weather(type), Wind(avg/gust), Precipitation(24-h), Sun(%), Sky(cover), River(height),Ice(thick), Pressure(avg sta/avg sea)
TD-3240	Hourly Precipitation	Hourly Daily	Precip(1-hr, 24-h totals)
TD-3260	15 Minute Precipitation	15-min Daily	Precip(15-min, 24-h totals)
TD-3280	Surface Airways Hourly	Hourly	Cloud(Amount,ceiling,type), Visibility(horizontal), Wind(speed/direc), Temp(dry/wet/DewP), Sky(cover), Relative Humidity(%), Pressure(sta/sea/alt), Present Weather(type)

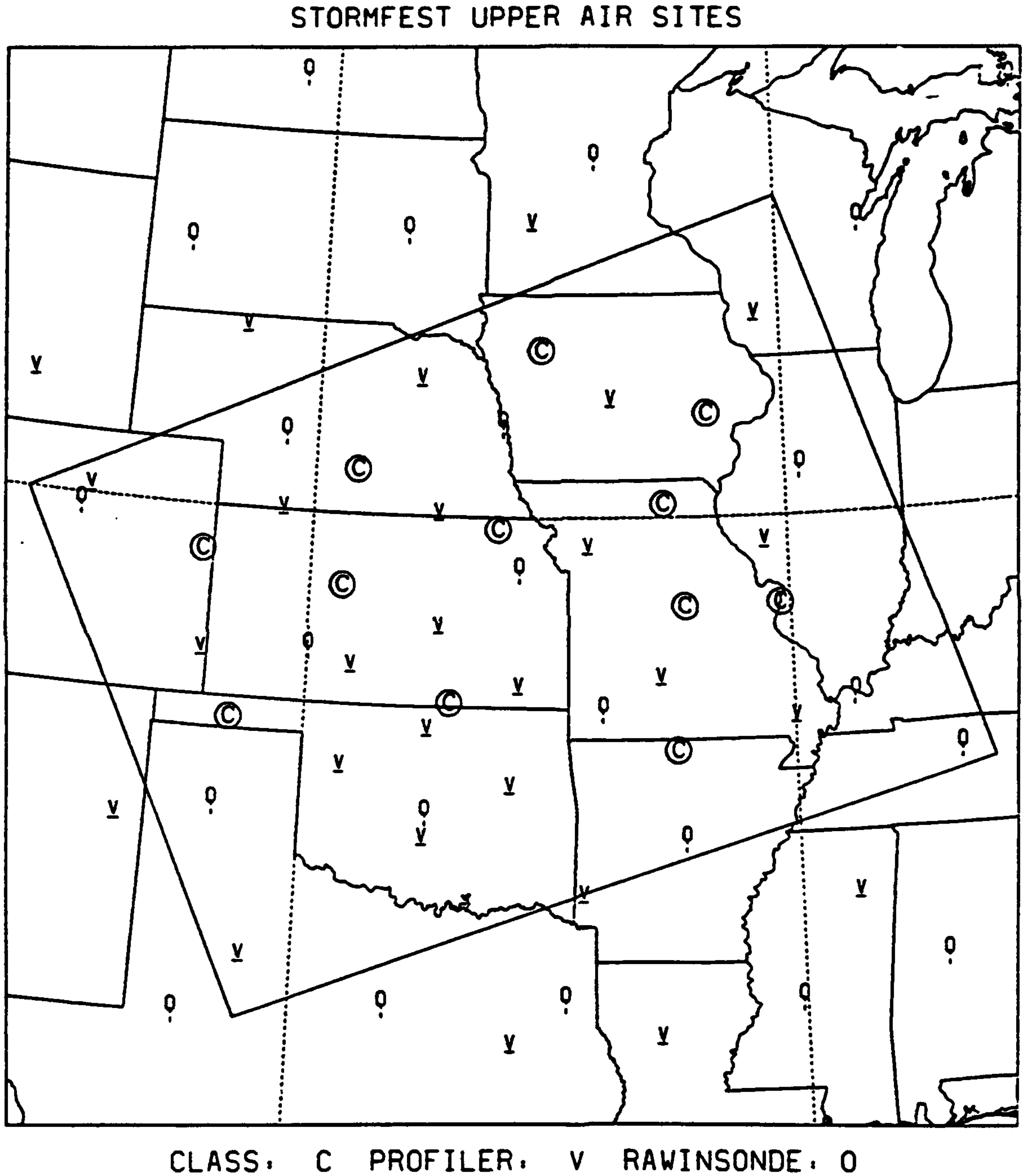

Figure 8. STORM-FEST upper air stations for the Inner Network.

* A number of other previous field programs have been run that may provide sources of data and will also be considered (Table 8).

Table 8. Summary of additional archived field program data sets under consideration for use in C&V physical model development.

Name	Date	Location	Comments
Cabauw/E	1977 - 1979	Cabauw, Holland	Includes tower data
COAST	May 1983	Dutch coast	Coastal Wx
Øresund	Summer 1984	Denmark & Sweden	Water & land
GALE	January - March 1986	Eastern USA, Atlantic	No soil or ground data
HAPEX	May-July 1986	SW France	Over land only
HEXOS	Autumn 1986	North Sea	Over ocean only
Various	1970s - present	US and Foreign	FAA Icing Program

Field experiments planned within the next few years could potentially provide data sets useful to C&V algorithm development. These include the *Global Energy and Water-Cycle Experiment (GEWEX)*, *STORM I*, and the Naval Research Laboratory's *Coastal Meteorology Accelerated Research Initiative* field experiments.

It should be emphasized that, while these data sets may be useful in helping to develop a prototype model system and in understanding PBL processes in general, they cannot substitute entirely for test bed data. The main problem is the lack of sufficient cases with which to develop and test statistically-based short-term prediction algorithms.

Current Real-Time Operational Data Sets

Data available on the current operational circuit comes from the familiar sources of rawinsondes, ocean buoys, direct surface observations, and selected National Meteorological Center (NMC) operational model grid point data sets. As was mentioned in Section IV, standard real-time operational data sets are incomplete with respect to many of the variables that would be desirable for a close evaluation of the physical column model, C&V algorithm performance and related analyses. They do, however, have the advantage of being readily accessible, and also they provide an opportunity for testing real-time prototype systems. Several sources of these data are available:

- *Commercial Real Time Databases (WSI, Kavouras, Alden/Zephyr, etc.)* - These vendor data sets are the conventional National Weather Service data usually held for 24 hours and can be accessed via modem, satellite dish, or other communication medium.

- *National Center for Atmospheric Research (NCAR) and National Climatic Data Center (NCDC)* - Most of the same data sets available in real time are archived by NCAR in Boulder, CO and NCDC in Asheville, NC. One advantage to accessing data sets from either of these two sources is that they are usually quality-controlled and include more complete digital data from NMC's operational models. A disadvantage is that archived data is sometimes incomplete; for example, specials from the surface observations (SAOs) are usually not included in the archive.

V. SUMMARY

This report provides the scientific basis for the data required to support the development of ITWS Ceiling and Visibility (C&V) products. An attempt has been made to reconcile the most idealized specification of data with those that may be sufficient for both statistical and physical model approaches. This is done in the context of the phenomena that are the primary cause of C&V degradation at several candidate ITWS C&V sites. A qualitative description of these phenomena has been provided. Alternative data sources, including archived field experiment and real-time data sets, have also been summarized.

ACRONYMS AND ABBREVIATIONS

AAR	Airport Acceptance Rate
ACARS	Aircraft Communications Addressing and Reporting System
AGL	Above Ground Level
ARINC	Aeronautical Radio Inc.
ARTCC	Air Route Traffic Control Center
ASOS	Automated Surface Observation System
ASRC	Atmospheric Sciences Research Center (SUNY, Albany, NY)
ATD	Atmospheric Turbulence and Diffusion
AWIPS	Advanced Weather Interactive Processing System
AWOS	Automated Weather Observation System
CASH	Commercial Aircraft Sensing Humidity
CCN	Cloud Condensation Nuclei
CLASS	Cross-chain Loran Atmospheric Sounding System
CWSU	Center Weather Service Unit
C&V	Ceiling and Visibility
ERL	Environmental Research Laboratory
EWR	Newark International Airport
FAA	Federal Aviation Administration
FSL	Forecast Systems Laboratory
ft	feet
GEWEX	Global Energy and Water-Cycle Experiment
HPCN	High Plains Climate Network
IOP	Intensive Observation Period
ICN	Illinois Climate Network
ITWS	Integrated Terminal Weather System
JFK	New York - John F. Kennedy International Airport
km	kilometers
LAPS	Local Analysis and Prediction System
LCL	Lifting Condensation Level
LGA	New York - La Guardia Airport
LLWAS	Low Level Windshear Alert System
LWC	Liquid Water Content
m	meters
MAPS	Mesoscale Analysis and Prediction System
MDCRS	Meteorological Data Collection and Reporting System
MEM	Memphis International Airport
mesonet	mesoscale network
NCAR	National Center for Atmospheric Research
NCDC	National Climate Data Center
NEXRAD	Next Generation Weather Radar
NGM	Nested Grid Model
NMC	National Meteorological Center

NOAA	National Oceanic and Atmospheric Administration
NPAM	NCAR Portable Automated Mesonet
NSF	National Science Foundation
NWS	National Weather Service
NYC	New York City
ORD	Chicago - O'Hare International Airport
OSU	Oregon State University
PAM	Portable Automated Mesonet
PBL	Planetary Boundary Layer
RASS	Radio Acoustic Sounding System
RVR	Runway Visual Range
RWS	Rawinsonde
R_e	Equivalent droplet radius
SAO	Surface Aviation Observation
SAV	State-of-the-Atmosphere Variable
SFO	San Francisco International Airport
STORM-FEST	STORM - Fronts Experiment Systems Test
SUNY	State University of New York
SVAT	Soil-Vegetation Atmospheric Transfer
T-LAPS	Terminal LAPS
TDWR	Terminal Doppler Weather Radar
TRACON	Terminal Radar Approach Control
UQAM	University of Quebec at Montreal
USWRP	US Weather Research Program
WSR-88D	Weather Surveillance Radar - 88 Doppler
1DPBL	One-Dimensional Planetary Boundary Layer
4DDA	Four-Dimensional Data Assimilation

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APPENDIX

Other Institutions Developing Relevant Technologies

An assessment of technology on a global scale is being made as part of the C&V product development to take advantage of relevant ongoing efforts at other institutions. The current list of institutions known to be active in areas of science and technology relevant to supporting ITWS product algorithm content or system design includes:

Atmospheric & Environmental Research Inc. (AER)
- Adjoint applications for optimizing column models

Atmospheric Sciences Research Center, State University of New York (ASRC/SUNY)
- Sensor technology
- Test bed design strategy

Colorado State University (CSU)
- Adjoint applications for Column models
- Visibility and liquid water droplet distribution
- Cloud processes

European Center for Medium-Range Weather Forecasting (ECMWF)
- Kalman filtering techniques for site-specific forecasts

Florida State University
- PBL Cloud (OSU1DPBL adaptation)

National Center for Atmospheric Research, Research Application Program (NCAR/RAP)
- Aviation Weather Products Generator (AWPG)

Naval Research Laboratory (Monterey, CA)
- Artificial Intelligence techniques for marine fog forecasting

New Zealand Meteorological Service
- PBL Cloud (OSU1DPBL adaptation)
- Evaluating Meteo France's fog model for aviation applications

NOAA /Air Resources Laboratory (NOAA/ARL)
- Column model for air quality monitoring
- Four-dimensional data assimilation

NOAA Forecast Systems Laboratory (NOAA/FSL)
- Aviation Gridded Forecast System (AGFS)
- Weather workstation technology

NOAA/NMC Ocean Products Center
- Operational advective sea fog model

Meteo France
- Coupled mesoscale / column model for site-specific fog forecasts
- Test bed and operational sensor suite / design strategy experience
- Land surface parameterizations
- Weather workstation technology

Oregon State University
- PBL Column model (OSU1DPBL)

Pennsylvania State University (PSU)
- Four-dimensional data assimilation
- Mesoscale modeling
- PBL parameterizations
- Soil moisture flux models

Phillips Laboratory
- Physical diagnostic fog models (OSU1DPBL adaptation)

San Jose State University / SRI International
- Expertise in San Francisco bay area wind and marine stratocumulus
- Surface wind model

Royal Dutch Meteorological Institute (KNMI)
- Lagrangian vertical structure column model

UK Meteorological Office (UKMO)
- Lagrangian vertical structure model (KNMI model)
- Fog and stratocumulus modeling

University of Quebec at Montreal (UQAM)
- Remote sensing of clouds
- Diagnostic Models of low cloud
- Planetary Boundary Layer (PBL) Processes

University of Wisconsin (Madison)
- High-resolution, nonhydrostatic PBL model (weakly convective)